Direct Numerical Simulation of Tilted Rayleigh-Taylor Instability

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Rayleigh-Taylor instability (RTI) with tilted initial interface is investigated using Direct Numerical Simulation (DNS). Due to the novel nature of this flow and its importance in turbulence modeling, our simulations are also being proposed as a standard test problem for LANL codes. Our DNS results compare well with laboratory experiments for appropriately chosen initial conditions, both qualitatively and quantitatively. In general, this is a non-trivial task as there is a long-standing discrepancy between the experimental and previous numerical results of RTI-related problems. We find that the global motions in tilted RTI can be decomposed into three components: 1) rotation (overturning) of the interior interface, 2) mixing of the interior interface, and 3) development of side-wall bubble/spike. The fundamental dynamics and scaling of each component have been determined. The effects of initial conditions have also been identified.

Rayleigh-Taylor instability (RTI) is an interfacial instability that occurs when a high-density fluid is accelerated or supported against gravity by a low-density fluid. This instability is of fundamental importance in a multitude of applications, ranging from fluidized beds, oceans, and atmosphere, to inertial confinement fusion (ICF) and supernovae. Because of both its scientific and practical importance, RTI has been subjected to intense research over the last 50 years. However, previous studies, experimental or numerical, have been focused on the canonical RTI in which the perturbations are on a perfectly horizontal plane. On the other hand, in most real world applications, the initial perturbations are rarely on a perfectly horizontal plane.

In tilted RTI, the inclination of initial interface causes a large-scale overturning motion in addition to the buoyancy-driven instability. As a result, turbulence in tilted RTI is generated through two mechanisms: buoyancy and shear. The overturning of the interface also causes the mean flow to be 2D, instead of 1D as in the canonical RTI. These features make tilted RTI an excellent modeling test, and also an excellent way to study the physics of turbulence production, by contrasting the two common turbulence generation mechanisms.

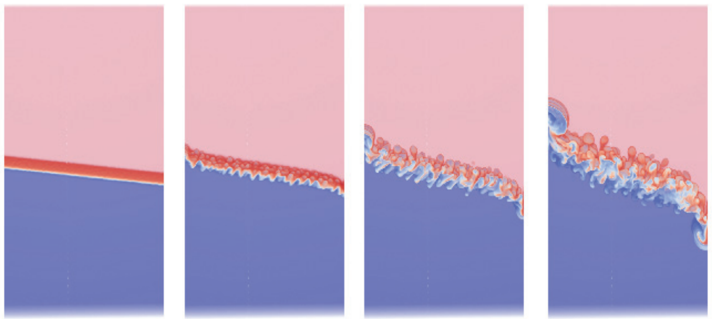

Fig. 1. Three-dimensional view of tilted RTI evolution. From left to right: 0 ms, 26 ms, 36 ms, and 46 ms. Heavy fluid (red color) sits on top of light fluid (blue color).

Previous researches on tilted RTI have been limited to the experimental [1–3]. Here we present the first extensive studies of tilted RTI using direct numerical simulation (DNS). The DNS code we use is the CFDNS developed by Livescu et al. [4]. Numerical details and verification and validation of the code are referred to in [4,5]. Simulation parameters were chosen to match those of Rocket-Rig experiments [1]. Figure 1 shows the evolution of tilted RTI from a typical DNS simulation. Acceleration is in the vertical direction (x-direction), pointing downwards. Heavy fluid (1890 kg/m^3) is sitting on top of the light fluid (660 kg/m^3), and the Atwood number is about 0.48. The mean acceleration is about 35g_0. Initial perturbations are on an interface tilted 5.77 degrees away from the horizontal plane (y-direction). Periodic boundary conditions are used in the z-direction (Fig. 1).

As time progresses from left to right across Fig. 1, the angle between the interior interface and horizontal plane grows continuously, until the interior interface finally becomes perpendicular to the horizontal plane. In the meantime, small perturbations on the interior interface grow due to buoyancy as in the canonical RTI. As shown in Fig. 1, bubbles and spikes of various sizes develop along the interior interface, and interact with each other. The overturning of the interior interface also causes an increase of shear within the interface, resulting in another mechanism of instability development. In contrast, the instability next to the sidewall develops quite differently from that of the interior domain. Due to the blockage of the wall, the instability next to the sidewall develops into a single "quasi-2D" bubble/spike. The growth in these regions is through a new mechanism, discovered in a separate study, through complex vortical interactions [5]. In summary, the global motions in tilted

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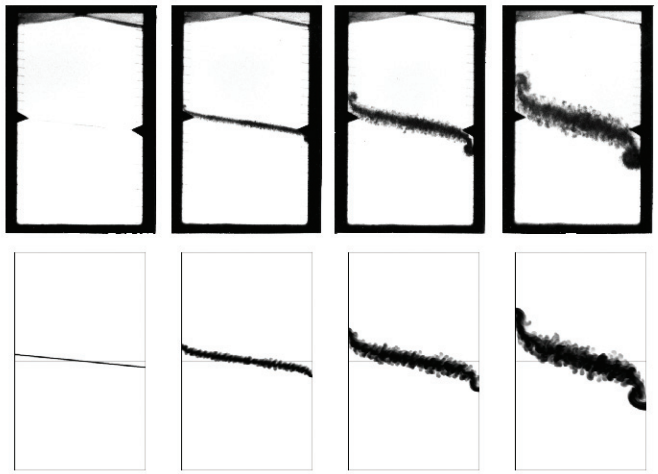

Fig. 2. Comparison between experiment (Rocket-Rig experiment number 110) and DNS. From left to right: 0 ms, 26 ms, 36 ms, and 46 ms.

RTI can be decomposed into three components: 1) rotation (overturning) of the interior interface, 2) mixing of the interior interface, and 3) development of the side-wall bubble/spike. The underlying dynamics and scaling of each component are different [6].

Our DNS results are compared, qualitatively and quantitatively, with laboratory experiments in Figs. 2 and 3. In Fig. 2, images at four instants (0 ms, 26 ms, 36 ms, and 46 ms) are compared between DNS and Rocket-Rig experiment number 110. As the figure shows, our DNS results agree well with experimental observations, including the angle and mixing of the interior interface, as well as the sidewall bubble/spike development. The agreement of the interior interface rotation can be better seen in Fig. 3, which compares the angle of the interior interface between DNS and experimental data from two independent sources [1,3]. Nevertheless, unlike experiments where only measurements of global quantities are available, all turbulence statistics necessary for model development or investigation of the turbulence physics are available from DNS. As shown in Fig. 3, the proper time scale for the rotation of the interior interface is $\sqrt{L_h / g}$, where L_h is the horizontal domain size and g is the acceleration.

In DNS, the initial conditions are precisely specified, making DNS the ideal tool to study the effects of initial conditions. The related parameters we have examined include the initial perturbation Reynolds number, the spectrum shape and amplitude of initial perturbations, and the initial tilting angle. The initial conditions have different roles in the three components of the global motions. For example, we find that the rotation of the interior interface is strongly influenced by the initial tilting angle, but not by the other parameters. In contrast, the mixing within the interior interface is strongly influenced by the initial perturbation Reynolds number.

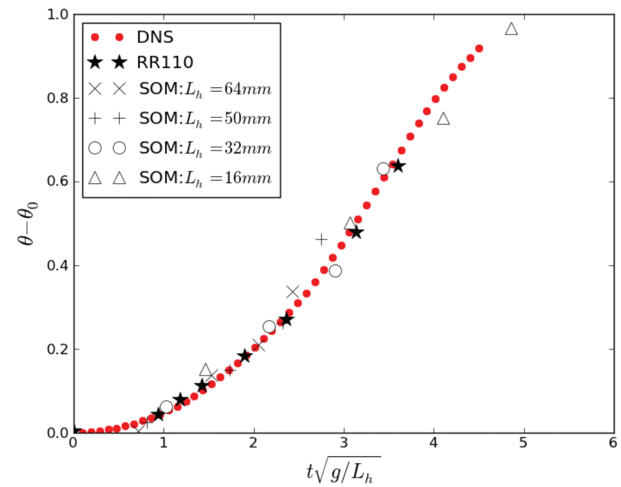

Fig. 3. Comparison of the interior interface angle between experiments and DNS. Experimental data are from two sources: Rocket-Rig experiments (RR110) [1] and SOM experiments [3]. In SOM, experimental apparatus of four horizontal domain sizes (16 mm, 32 mm, 50 mm, and 64 mm) were used.

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